CHAPTER 4

GLOBAL WATER AND ENERGY CYCLE

4.0 INTRODUCTION

The cycling of water in the Earth's atmosphere is the process that constantly renews fresh water resources, a feature unique to our planet. As civilizations evolved, the human population, agriculture, and industry have placed ever-increasing demands on water resources and, by now, significant change in the global hydrologic regime would entail serious consequences in many regions where water resources are already strained.

The National Research Council report on *Research Pathways for the Next Decade* recognized the global water cycle as a central research issue of global environmental change: "Water is at the heart of both the causes and the effects of climate change. It is essential to establish current rates of, and possible changes in precipitation, evapotranspiration, and cloud water content… Better time series measurements are needed for water runoff, river flow and… the quantities of water involved in various human uses" (NRC, 1999). Ascertaining the rate of cycling of water in the Earth system, and detecting possible changes, is a first-order problem as regards the renewal of water resources.

Rainfall and subsequent fast hydrologic processes are directly linked to the development and life cycle of weather systems. Conversely, the latent heat transported and released by the global water cycle is the principal source of energy that drives the atmospheric circulation and weather disturbances, over periods of hours or days, and horizontal scales of 10-100 kilometers. Thus, a fundamental problem is that of relating planetary-scale climate variations or change to regional weather and fast hydrologic processes that directly control water resources. Scientific progress in this domain is critically dependent upon the ability to observe the atmosphere and Earth surface at high spatial and temporal resolution, and the ability to handle the resulting large data flows and long time-series. NASA capabilities are well suited to undertake both tasks.

Net radiation absorbed by the Earth's surface is the energy source that drives evaporation and, in general, the global water cycle. In this respect, water and energy exchanges are complementary aspects of the same global process. Furthermore, water in the form of vapor, cloud ice or cloud liquid water, controls atmospheric radiation transfer, the planetary radiation balance, and climate. In the words of the Intergovernmental Panel on Climate Change (IPCC, 1996): "Uncertainties in modeling cloud-radiation interactions are the largest factor in determining the range [of climate warming]". A decade of scientific research and technology development conducted under NASA's Earth Observing System (EOS) program has enabled embracing the spatial diversity and complexity of these cloud and radiation feedback processes (EOS Science Plan: *Radiation, Cloud, Water Vapor, Precipitation and Atmospheric Circulation*; NASA, 1999).

This cross-cutting research theme builds upon the progress made by the Global Energy and Water Cycle Experiment (GEWEX) of the World Climate Research Program, and the Biospheric Aspects of the Hydrological Cycle (BAHC) project of the International Geosphere-Biosphere Program. The goals of NASA in this domain are to conduct an interdisciplinary research effort in cooperation with USGCRP partners, and make key scientific contributions based on NASA's unique capabilities for global observation, data analysis and Earth system modeling. The overarching goal is to improve the understanding of the global water cycle to the point where useful predictions of regional hydrologic regimes can be made. This predictive capability is essential for practical applications to water resource management and for validating scientific advances through the test of real-life prediction.

4.1 MAIN SCIENCE QUESTIONS

- ***How are global precipitation, evaporation, and the cycling of water changing? (Variability)***

According to model predictions, the most significant manifestation of climate change would be an acceleration of the global water cycle, leading to increased global precipitation, faster evaporation and a general exacerbation of extreme hydrologic regimes, floods and droughts. Since the release of latent heat associated with condensation is the principal source of energy for rapid cyclogenesis, a more active water cycle would generate more frequent and/or more severe weather disturbances. Paleoclimatic and historical records indicate the occurrence of devastating floods and droughts in past times but these ancient hydrologic events do not constitute compelling evidence of global change in the hydrologic cycle, as most regional anomalies are just manifestations of local weather variability. Knowledge of global atmospheric energy and water budgets, as well as global precipitation, is needed in order to investigate the existence of significant global trends in the rate of the water cycle.

- ***What are the effects of clouds and surface hydrologic processes on the Earth's climate? (Response)***

The overall response of mean climate properties to changes in external forcings is the result of a multiplicity of non-linear "fast climate processes" that evolve on meteorological time-scales in the atmosphere and at the surface of the Earth. Such processes ultimately determine time- and space-averaged climate properties and the relationships between these properties. On the other hand, empirical relationships between climatological mean properties provide little insight in the underpinning fast physical, chemical and biological processes that govern momentum, energy and water exchanges in the climate system. Knowledge of these basic processes is essential to extrapolate confidently model simulations from current climate conditions to significantly different states of the Earth system. The problem is integrating the results from observation and model studies of cloud systems, atmospheric boundary layer turbulence, land surface processes and watershed hydrology, and surface fluxes over ocean and continents in order to develop reliable mathematical representations of these small-scale physical processes in atmospheric circulation and climate models.

- ***How are variations in local weather, precipitation and water resources related to global climate variation? (Consequences)***

A critical problem of climate science is that of relating changes in global-mean climatological state to variations in the probability and intensity of weather phenomena, and related changes in precipitation, hydrologic regimes of river basins, and fresh water resources. Soil moisture, accumulated snow, and the freeze/thaw transition control evaporation, surface temperature, and climate as well as the growth of plants. This new climatic outlook at hydrology, enabled by global observation of hydrologic parameters from space, aims to achieve quantitative predictions of precipitation and run-off on all spatial scales, from global to the scale of individual river catchments that are relevant to water resource management. Essential for achieving this objective is the capability to observe and model the global atmospheric circulation and land surface hydrology at much higher spatial resolution than is currently practical with climate models.

- ***How well can weather forecast duration and reliability be improved by new space-based observations, data assimilation, and modeling?*** **(Prediction)**

Accurate forecasting of weather has major significance for the protection of lives and property. Thus, improving the accuracy of short-term predictions and increasing the period of validity of long-range forecasts is of great practical interest and is also a great scientific challenge. Scientific advances in climate and/or atmospheric general circulation models, and more effective methods for ingesting new types of observations, are directly applicable to the improvement of operational forecasting systems. Conversely, experience has shown that synergy with operational weather forecasting is a powerful engine of progress for both the verification of new scientific concepts and the development of new observing systems or products.

4.2 NATURE AND SCOPE OF THE SCIENTIFIC PROBLEM

Evaporation, precipitation and the transport of water in the Earth's atmosphere are the controlling processes that redistribute energy from the Sun, drive the atmospheric circulation and renew fresh water reserves. Current knowledge of these complex processes is not accurate enough to predict with confidence the amount of rain nor the mass budget of water reservoirs.

4.2.1 Global Water Cycle Variability and Trends

A statistically meaningful rise in global mean temperature (with significant regional differences) has been observed at the surface of the Earth during the last century, particularly the last two decades. Surface warming implies a rise in the temperature of all or part of the atmospheric column, an increase in atmospheric water content, and changes in atmospheric circulation that are manifested by a global pattern of warming and cooling. While still relatively small, such large-scale or global climate changes can and do entail changes of much greater significance in regional weather, ecosystem productivity, water resource availability, and other attributes of the environment.

Atmospheric temperature implicitly determines the large-scale atmospheric flow, including dynamical instabilities that are at the origin of weather phenomena. Atmospheric water vapor is the principal vehicle of the atmospheric energy that drives the development of weather systems and the source of precipitation. Further, water vapor is a strong absorber of terrestrial radiation; increased atmospheric moisture associated with warmer air has a powerful amplifying impact (positive feedback) on the greenhouse effect. Global temperature and moisture profile measurements are obtained routinely by operational environmental satellites, but the existing operational measurements do not provide the accuracy and consistency required for climate research. Improved measurements are required to address this scientific problem and would also be of direct benefit for weather forecasting applications.

Global precipitation is the principal indicator of the rate of global water cycle, and can also be used effectively as an input for numerical weather forecasting. Together, the atmospheric water content and global precipitation rate determine the residence time of water in the atmosphere. Precipitation data, obtained routinely by a worldwide network of land-based raingauges, show evidence of increasing rainfall rates in some regions. In other regions, notably the tropical oceans, knowledge of precipitation rates is poor due to the limited observational base. Establishing the existence of a global trend requires homogeneous global rainfall information that can only be assembled from a combination of surface-based and space-based measurements.

Closing the water budget over all regions of the world is the ultimate objective of water and energy cycle research. Indeed, knowledge of net fresh water fluxes over the world oceans is indispensable not only to close the atmospheric leg of the global water cycle, but also to quantify fresh water inputs or losses that control ocean water salinity and density. The "buoyancy flux" associated with net fluxes of heat and fresh water is the principal driver of the deep ocean circulation. Likewise, changes in regional precipitation and evaporation drive variations in hydrologic regimes, water resources, and soil moisture available for plant growth. Over polar and high altitude regions, solid precipitation (snowfall) minus sublimation, snow and ice melting, or iceberg discharge control the mass balance of glaciers and polar ice sheets, the latter containing a significant fraction of the Earth's total reserve of free water. The overall goal is to deliver reliable estimates of precipitation minus evaporation over the whole surface of the Earth, likely from a combination of measurements (principally precipitation) and model estimates (principally evaporation).

4.2.2a Water Vapor, Clouds, and the Planetary Radiation Balance

Water vapor strongly absorbs infrared radiation and provides by far the largest contribution to the atmospheric greenhouse effect, nearly 90 Watt/m^2 compared to 30 Watt/m^2 for all other absorbing trace gases present in the atmosphere. Furthermore, atmospheric humidity is highly variable and responds strongly to changes in atmospheric temperature, thus inducing a potent feedback mechanism that tends to amplify climate change. However, the physical processes that control the distribution of water vapor are not known well enough to ascertain beyond doubt whether, for example, deep convection has a net moistening or drying effect on the upper troposphere. Existing water vapor data are neither accurate nor comprehensive enough to establish the existence of a systematic trend associated with global climate change.

Liquid water or ice clouds profoundly affect the planetary radiation budget: clouds contribute about 50% of the planetary albedo, and absorption of terrestrial radiation by cloud is equivalent to all greenhouse gases other than water vapor. Clouds also are the principal factor controlling instantaneous radiant energy fluxes that are absorbed by the atmosphere or the Earth surface. Radiative heating or cooling of the atmosphere cause air parcels to rise or sink and, in general, trigger convective motions. Net radiation absorbed by the Earth's surface is the basic energy source that drives evaporation, and fuels photosynthesis. Because of the complexity of cloud microphysical processes and extreme variability of cloud systems, the goal of relating the radiative impact of clouds to basic physical knowledge has eluded us so far. The formation, life cycle and optical properties of cloud systems remains, to this day, the largest source of uncertainty in simulations or predictions of global climate change. Clouds affect climate both directly, through their controlling effect on the planetary radiation balance, and indirectly, through vertical transport and condensation of water vapor that controls upper-tropospheric moisture and its greenhouse effect. Conversely the formation, life cycle and radiative properties of clouds are governed by the relative humidity of surrounding clear air.

Cloud processes involve complex 3-dimensional interactions between fluid dynamical motions, microphysical and optical properties of liquid and ice cloud particles, pre-existing condensation nuclei (aerosols), and the dynamics of the mesoscale weather systems in which they are embedded. These complex interactions generate extremely diverse cloud systems and cloud types, each involving different controlling microphysical and meteorological factors. Understanding these complex phenomena requires observations that simultaneously (1) resolve the 3-dimensional structure of cloud systems, (2) cover a representative sample of all different cloud types, (3) characterize large-scale weather patterns or mesoscale disturbances that generate the clouds, and (4) relate cloud system structure and properties to large-scale climate variables, especially divergent winds in the troposphere and radiation fluxes at the top of the atmosphere. These observational requirements have only been partially met so far by field observation campaigns focused on one or a few cloud types. NASA is preparing a major space-based exploratory program, involving a constellation of three experimental satellites, to provide for the first time this full range of observations.

4.2.2b Surface Hydrology, Water Resources and Biospheric Processes

Fresh water is an essential ingredient of life, indispensable to all terrestrial species and an essential resource for agriculture. Water also plays a unique and almost irreplaceable role for a very broad range of domestic applications and industrial processes. For these reasons, fresh water is an immensely valuable resource on which our existence depends. The long-range transport of water vapor by winds, condensation and precipitation, the partitioning of rainfall between ground water storage and river runoff, and evapotranspiration from vegetated areas, all contribute to determining the fresh water budget of land areas, and the fate of water reserves available to terrestrial ecosystems and human societies. These diverse phenomena have yet to be quantified with sufficient accuracy to enable applying existing climate predictions to flood forecasting and water resource management.

The ***surface hydrologic processes*** that govern continental water budgets and the availability of fresh water resources are the result of complex physical and biological processes taking place at the land surface. So far, basic hydrologic processes have been examined mainly at the scale of relatively small river basins or catchments. Quantitative understanding of hydrologic processes over large areas, commensurate with the scale of climate phenomena, will require a breakthrough in large-scale observation of hydrologic properties and physical climate drivers. Specific observational requirements to address this problem include (in addition to atmospheric properties, precipitation and surface radiation fluxes) exploratory measurements of soil moisture, snow accumulation, and the transition between frozen and thawed soil conditions.

From a broader perspective, the Earth system can be envisioned as consisting largely of interconnected cycles for water, energy, and carbon. Hydrologic processes play a central role in connecting the three cycles across land, atmosphere and ocean. Soil moisture controls land evaporation and plant transpiration, two processes that links the fluxes of energy (radiant and latent heat), water and carbon between land and atmosphere. River flow carries nutrients and sediments to estuaries, providing an effective link between terrestrial and oceanic systems. Traditionally Earth sciences have progressed along disciplinary lines that address research questions within one geographical domain and often only one (or two) of the above cycles. As our interdisciplinary understanding of the Earth system progresses, many productive science questions are emerging concerning the interfaces between the water, carbon, and energy cycles and between the atmospheric, terrestrial, and oceanic domains.

4.2.3 Climate-Weather Connections

Weather disturbances and, in general, the atmospheric circulation govern the distribution of clouds, their water content, precipitation yield and radiative properties. It is not sufficient, for climate predictions, to study atmospheric or land surface processes in isolation from the atmospheric circulation which controls the water and energy inputs to these processes. Such connections are transient and can only be understood, modeled, and validated through direct comparison of meteorological and hydrological model products with observations at the same place and time. This opportunity is lost when research is limited to studies with atmospheric circulation models unconstrained by observed initial values.

To what extent are variations in local weather, precipitation and water resources related to global climate change? The striking manifestations of "El Niño weather" are clear examples of the linkage between a large-scale or global climate anomaly and changes in regional weather patterns. Much remains to be learned, however, about the relationship between observed trends or anomalies in global-mean atmospheric state and changes in the path, frequency and intensity of weather systems. The broad scientific challenge is that of relating the large-scale atmospheric circulation to the dynamics and life cycle of mesoscale storms (e. g. hurricanes) and other severe weather systems (e. g. tornado-generating rainstorms), and then predicting how that relationship might change in different future climates. The specific challenge is that of deriving quantitative precipitation predictions from global and/or mesoscale weather models. Both topics are also central objectives of the US Weather Research Program.

A major anticipated impact of global climate change is change in the frequency and severity of regional floods and droughts, the availability of water resources, and the volume of inland water bodies (e. g. the Caspian sea). Again, the principal driver of these changes is precipitation, but knowledge of large-scale changes in soil moisture, snow accumulation, seasonal soil freeze/thaw transitions, and the stage height of large rivers and inland water bodies, is also required to gain quantitative insight in the hydrologic consequences of climate variability and change. As competition for water resources rises, this information will become increasingly valuable for rational management of limited water resources.

4.2.4 Extended-Range Weather Prediction

Improving the accuracy of short-term forecasts and increasing the period of validity of long-range predictions both are of great practical interest for the protection of lives and property. Both objectives are also great scientific challenges. Thus, the question arises: To what extent can weather forecasting be improved by new global observations and advances in satellite data assimilation?

Twenty years ago, meteorologists had their first opportunity to use of global satellite observations collected for the scientific purpose of demonstrating the feasibility of one-two week weather prediction using computer models of the atmosphere. We are now finally on the verge of achieving this objective, thanks to successive breakthroughs in global weather observations, atmospheric circulation models, and data assimilation methods used for ingesting observations into such models.

Space-based measurements can only detect radiation emerging from the earth's atmosphere, not determine directly the meteorological properties of interest. The interpretation of satellite measurements is basically a two-step mathematical procedure: (1) inferring the properties of the atmospheric medium from the observed radiation signature, and (2) merging the new data with other measurements at different locations and times, including information from past measurements that is contained in the current predicted state of the atmospheric circulation. These two steps may be combined into a single retrieval/4-dimensional assimilation process, as computing capabilities would permit. In-depth knowledge of the physics of the measurement is essential for succeeding in the first task, that can be provided by instrument science teams associated with NASA development projects.

While weather prediction is the primary responsibility of operational environmental agencies, such as NOAA in the US, scientific advances made by NASA in the development of new observation techniques, more realistic climate or Earth system models, and more effective methods for ingesting new types of observations, are directly applicable to the improvement of operational forecasting systems. Experience has shown that synergy between operational weather forecasting practice and the development of new observation systems or products is an effective engine of progress for both. The principal thrusts of ESE's cooperation with operational weather services are (1) participation in the development of precursor operational instruments for application to various operational environmental satellite systems, (2) development of new data products originating from space-based observing systems, and (3) collaboration in the development and experimentation of improved atmospheric circulation models and data assimilation schemes.

EXPECTED SCIENTIFIC ACHIEVEMENTS

Question 1: How are global precipitation, evaporation, and the cycling of water changing?

Expected new knowledge in the next 5 years

- Decadal trend in total precipitable water over the oceans, based on a ten-year global data set of microwave radiometric measurements;
- Baseline 3-dimensional distribution of water vapor in the global atmosphere;

Expected new knowledge in the next 10 years

- Decadal trend in the water vapor content of the global troposphere (by altitudes and regions) based on a ten-year high-resolution data set;
- Decadal trend in global rainfall rate, based on a ten-year data set.

Question 2: What are the effects of clouds and surface hydrologic processes on the Earth's climate?

Expected new knowledge in the next 5 year

- Global statistics of 3-dimensional cloud structure and cloud particle properties over a representative set of weather systems; and impacts on the planetary radiation budget;
- Cloud Ensemble Model simulations of cloud dynamics and microphysics and application to parametric representation of clouds in climate models, especially tropical cirrus clouds.

Expected new knowledge in the next 10 years

- Model representation of radiation transfer in the cloudy atmosphere and estimation of surface radiation at the level of accuracy needed for predictions of regional climate change;
- Indirect radiative forcing due to the effect of aerosols on cloud radiative properties.

Question 3: How are variations in local weather, precipitation and water resources related to global climate variation?

Expected new knowledge in the next 5 years

- Relationship between sea surface temperature anomalies and tropical cyclone frequency;
- Relationship between global anomalies in surface boundary conditions and extra-tropical storm tracks, continent-scale precipitation, and river discharge.

Expected new knowledge in the next 10 years

- Relationship between seasonal anomalies in surface boundary conditions and ocean heat content and tropical cyclone intensity/precipitation;
- Time-dependent distribution of soil wetness over continents and estimation of volumetric soil moisture;
- Linkages between anomalies in land and sea surface conditions and regional or catchment-scale precipitation, soil moisture, and river discharge;
- Effects of the soil freeze/thaw transition on continental scale hydrology and ecosystems.

Question 4: How well can weather forecast duration and reliability be improved by new space-based observations, data assimilation, and modeling?

Expected new knowledge in the next 5 years

- Impact of improved (1°C/1km) temperature profile accuracy on weather forecasting skill;
- Impact of high-resolution ocean surface wind observation on the prediction of storm paths and storm strength;

Expected new knowledge in the next 10 years

- Impact of advanced atmospheric general circulation models and data assimilation methods on the skill of extended-range weather prediction
- Impact of global precipitation observations on the prediction of river flow and water resources.

4.3 NASA PROGRAM ELEMENTS

The pathway toward understanding the global water cycle and ultimately its role in climate is an integrative research strategy covering a range of atmospheric and land hydrological processes, which all have in common their dependence upon the atmospheric circulation and weather disturbances. Because of the short time-scales and spatial variability of meteorological phenomena, high resolution and frequent observations are needed, which places a heavy observational burden on the program, as emphasized in the EOS Science Plan, Chapter 2: *Radiation, Clouds, Water Vapor, Precipitation, and Atmospheric Circulation* (NASA, 1999).

Investigating trends in the rate of the global water cycle and atmospheric climate in general requires primarily consistent time series of global atmospheric temperature, moisture and precipitation data. To achieve this objective, significant improvement is required in the quality of basic atmospheric and hydrologic data sets acquired systematically by national environmental agencies. NASA will contribute to this enhancement by transferring scientific know-how and technical innovations from research programs to operational observing systems when the opportunity arises, such as the development of the National Polar-orbiting Operational Environmental Satellite System (NPOESS). The main thrusts will be (1) participation in the NPOESS Preparatory Project, including the development of an Advanced Technology Microwave Sounder, and (2) the realization a multi-satellite global precipitation measuring mission (Section 4.3.1).

The capability to accurately model the radiative effect of water vapor and clouds is a crucial requirement for climate predictions. The largest source of uncertainty in model simulations of global climate change is currently the representation of radiation processes in the cloudy atmosphere, characterized by the great complexity of radiation transfer physics, and spatial heterogeneity at all scales, from cloud particles to individual clouds and cloud systems associated with weather disturbances. NASA research will build on an already strong atmospheric radiation science program and focus on the study of generic cloud processes through (1) experimental satellite missions that aim to characterize the vertical structure of cloud systems, (2) *in situ* field studies of cloud physical properties and (3) the development of realistic 3-dimensional cloud ensemble models, with the objective of achieving vastly improved area-averaged representations of clouds and their effect on radiation transfer, atmospheric heating and the planetary radiation balance, suitable for incorporation in climate models (Section 4.3.2).

Surface hydrologic processes govern the partitioning of radiant energy between sensible and latent heat fluxes, thus controlling land surface temperature, evaporation and climate. Furthermore, the impact of weather and climate on water resources is governed by the partitioning of rainfall between evaporation, soil moisture and run-off. The partitioning is controlled by complex physical and biological land surface processes. Extensive observations of the relevant hydrologic properties are indispensable to characterize these processes on the global domain; NASA will combine the development of new experimental techniques for space-based measurement of basic hydrologic variables and properties, with a comprehensive program of field studies, data analysis and land surface process modeling and algorithm development (Section 4.3.3).

Investigating the relationships between large-scale climate and weather patterns must principally rely on numerical simulation with atmospheric circulation models (AGCM) that resolve weather systems, including relatively small-scale and severe weather phenomena (such as hurricanes and tornadoes). Essential for addressing these two objectives is the capability to acquire and analyze global atmospheric temperature, moisture, precipitation, and ocean surface wind data, the latter providing a direct measure of storm tracks, strength, and life cycle over the expanses of the ocean (Section 4.3.1). Another requirement is the capability to ingest and optimally assimilate a broad range of meteorological observations and derive reliable descriptions of both large-scale atmospheric climate and mesoscale storms (Section 4.3.4).

4.3.1 ATMOSPHERIC CIRCULATION DYNAMICS AND THERMODYNAMICS

Much of what we currently know or can infer about the general circulation of the atmosphere and the global energy and water cycle is derived from routine observations of basic meteorological variables: atmospheric pressure, temperature, moisture and wind. This information is obtained globally from a multiplicity of sources, notably *in situ* measurements by balloon-borne radiosondes and global remote sensing by operational meteorological satellites. A top scientific priority is to improve or develop space-based observing systems that can match the measurement quality now achieved only with dense *in situ* observing networks over limited regions. The NASA aims to develop advanced remote sensing systems and supporting scientific know-how, and to transfer these capabilities to operational observing programs, such as NPOESS, that can maintain observation continuity indefinitely in the future.

4.3.1.1 Systematic Global Atmospheric Measurements

Global Temperature and Water Vapor

Atmospheric temperature and moisture are the primary indicators of the state of the atmosphere. Consistent and accurate global temperature and moisture records are essential for identifying transient climatic variations and long-term trends, as well as more subtle changes such as variations in the vertical stratification or stability of the atmosphere. From an application perspective, global temperature and moisture are the primary state variables for initializing numerical weather prediction. Trace amounts of water vapor also play an important role in the chemistry of the stratosphere, in relation with stratospheric temperature and circulation; the corresponding scientific issues and NASA research strategy are discussed in Chapter 3.

The existing temperature and moisture "TIROS Operational Vertical Sounder" (TOVS) sensor system deployed on current polar operational environmental satellites is derived from original NASA instruments first flown on Nimbus-6 (1975) and TIROS-N (1978). A decisive breakthrough is expected with the Atmospheric Infra-Red Sounder (AIRS), which will be the first satellite sensor capable of emulating the accuracy of *in situ* temperature and moisture profile measurements. AIRS data will be available for the expected six-year lifetime of the EOS Aqua mission (2001-2006).

The long-term objective of NASA is to enable temperature and moisture measurements of quality similar to AIRS on operational environmental satellites. NASA is working with the NPOESS Integrated Program Office to promote this objective, and plans to participate in the development of a bridging mission for continued research-quality temperature and water vapor observation in the interim period between the termination of EOS Aqua and the first NPOESS mission. This NPOESS Preparatory Project (NPP) mission is described in Box 5. NASA recognizes that optimal exploitation of any satellite measurement requires sustained scientific investments, including validation and intercomparison studies, development of more accurate retrieval algorithms and re-processing of past data. NASA will continue to support research for validation and scientific exploitation of remote sensing data acquired by the NPP mission and following operational satellite systems.

NASA also intends to explore alternative measurement techniques, the most promising of which is based on precise determination of atmospheric refractivity profiles near the Earth limb from accurate measurements of the propagation delay of Global Positioning System (GPS) signals between any one member of the GPS constellation and satellite-borne receivers in low Earth orbit. GPS occultation measurement can provide accurate values of atmospheric density, pressure and temperature as a function of altitude with good vertical resolution but relatively modest horizontal resolution, from a height of about 30 km down to about 5 km. Because the absolute accuracy of GPS occultation measurements is limited only by the precision of atomic clocks, the technique is expected to provide a very consistent record of global atmospheric temperature, as needed to detect long-term trends. Further algorithm development and methodological studies will be needed to extract the full atmospheric information content of GPS occultation data, notably close to the Earth surface.

Box 5
NPOESS Preparatory Project (NPP)

From a NASA perspective, the NPP mission addresses the high-priority objective of maintaining the continuity of two critical EOS measurements in the post-2002 period. From the NPOESS perspective, the mission provides the opportunity to test in orbit two major new NPOESS sensor systems, as well as several innovative spacecraft technologies. The current plan is for a 5 year mission launched in 2005.

NPP embraces the objectives of the Global Terrestrial and Oceanic Productivity Mission (see Box 1) and will provide moderate-resolution multispectral imaging data across the visible and infrared spectrum, for a multiplicity of atmospheric, oceanic and land cover applications. This function will be provided by the Visible and Infrared Imaging Radiometer Suite (VIIRS) developed by the NPOESS program.

The NPP mission will also carry an advanced atmospheric sounder system, consisting of an infrared Fourier-transform spectroradiometer (Cross-track Infrared Sounder) developed by the NPOESS program, and an Advanced Technology Microwave Sounder developed by NASA. Altogether, the two sensors are expected to fulfill the EOS accuracy requirements for global atmospheric temperature and water vapor profiles measurements (1°C global RMS temperature accuracy in each 1km-layer of the troposphere).

In cooperation with several international partners, NASA is currently building an experimental constellation of five scientific satellites, each carrying a NASA-developed occultation GPS receiver. These international satellite missions of opportunity are Oerstedt (Denmark) and Sunsat (South Africa) launched in 1999, CHAMP (Germany) and SAC-C (Argentina) to be launched later in 1999, and GRACE (cooperative mission with Germany) to be launched in 2001. The next stage in the development of the radio-occultation technique may be a pre-operational constellation of dedicated satellites, proposed by an international consortium led in the USA by the University Corporation for Atmospheric Research, that would deliver GPS soundings in real-time for immediate assimilation in numerical weather prediction models.

Global Precipitation

Changes in the total amount and timing of precipitation directly affect runoff and the intensity of floods or droughts, as well as chemical processes in the air, biological processes on land and the oceanic circulation. Quantitative measurement of the time and space distribution of global precipitation is the next highest climate research priority after atmospheric temperature and moisture, and an essential requirement to understand the coupling among atmospheric climate, terrestrial ecosystems and water resources. Satellite remote sensing is the only means to acquire global rainfall data, considering the paucity of surface observations over the ocean and sparsely populated land areas.

Box 6
Global Precipitation Mission

The Global Precipitation Mission is meant to be a demonstration for a future operational global precipitation observing program combining passive and active microwave remote sensing techniques. The measurement methodology is based on frequent observations by a constellation of passive sensors, while detailed profile data will be provided by a common rain radar satellite for refinement and validation of retrieval algorithms for all spacecraft in the constellation. The observing system will consist of:

- A single "calibration" spacecraft carrying both an advanced rain radar and a multi-frequency microwave imaging radiometer.
- Two SSM/I sensors on operational DMSP satellites (to be replaced eventually by the multi-frequency Conical-scanning Microwave Imager-Sounder sensor on NPOESS),
- Four to six dedicated polar-orbiting spacecraft, each carrying identical or compatible microwave imaging radiometers, on staged orbits distributed so as to provide repeat observations at 3 hour intervals or less.

NASA will explore with international partners the means to implement such a multiple satellite system.

Precipitation information can be inferred from passive microwave imaging radiometer data acquired by existing operational environmental satellites (DMSP) and eventually NPOESS. Recent results from the Tropical Rainfall Measuring Mission (TRMM) show that the detailed cloud particle profile information provided by an active microwave sensor (Precipitation Radar) can be used effectively to improve the accuracy of rain rate estimates based on passive microwave measurements only. However, none of the existing or planned operational systems (nor *a fortiori* the single EOS Aqua mission) will provide sufficient sampling frequency globally (repeat interval of 3 hours or less) to capture the considerable spatial and temporal variability of precipitation events and provide a reliable estimate of total rainfall. NASA plans to seek the cooperation of international partners and deploy in the next five-to-ten years, an experimental satellite constellation that will achieve the required global coverage and sampling frequency for measuring global precipitation (See Box 6).

Global Tropospheric Winds

For over 20 years, researchers have been pursuing the development of Doppler lidar techniques for direct measurement of atmospheric winds in clear air. Direct observation of the global wind field would be extremely valuable for numerical weather prediction, as well as scientific diagnostics of large-scale atmospheric transport, weather systems, and boundary layer dynamics. Because of the lack of reliable, sufficiently dense, and accurate wind observations, uncertainties in model-derived estimates of divergent flow component of the global atmospheric circulation constitute a serious limitation in our understanding of the global energy cycle and the atmospheric transport of water, energy, and chemical species.

At present, however, the state of technology is such that a space-based Doppler lidar system could only deliver relatively sparse wind data, limited to air parcels where sufficient particulate matter tracers (aerosol or non-convective cloud) exist to produce a measurable backscatter signal. Such sparse wind vector measurements (even single component line-of-sight velocity data) could be assimilated by atmospheric general circulation models and would yield a significant incremental improvement in the quality of global analyses and numerical weather prediction, especially in the southern hemisphere and the tropics. On this account, the demonstration of Doppler lidar wind measurement from space could be a promising operational precursor mission. On the other hand, much technological progress leading to the development of more powerful, more energy-efficient and more reliable lasers is needed in order to realize the full potential of this active sounding technique for scientific research and applications.

Wind information can also be inferred from the motion of clouds (or patches of moist air) observed by geostationary satellites (see 4.3.1.3 below). Such measurements currently lack precision, especially in the assigned altitude level of the observed wind vectors but future high-resolution geostationary imager-sounder instruments may provide useful tropospheric wind profile information to follow, hour-by-hour the evolution of severe weather disturbances, notably hurricanes.

4.3.1.2 Global Air-Sea Fluxes

Knowledge of heat fluxes over the world ocean is essential in order to balance the global water and energy budgets. Accurate flux values can be derived from *in situ* measurements at a particular location or from an array of instruments such as may be deployed on the occasion of a major measurement campaigns at sea (e. g. TOGA-COARE). On the other hand, no existing surface- or space-based observing system can directly provide estimates of ocean basin-wide heat and water fluxes of sufficient accuracy for quantitative climate diagnostic study or prediction validation purposes. The most reliable global estimates of air-sea fluxes so far have been derived from operational global meteorological data assimilation and prediction products, using state-of-the-art atmospheric general circulation models. Such model products have reached the level of accuracy (residual uncertainty ~ 10 Watt/m^2) where meaningful heat and water budget closure experiments can be attempted over the area of an ocean basin.

Any additional observational information about the state of the atmosphere and the general circulation, that can serve to refine the knowledge of the "atmospheric demand" for water and heat, will contribute to inferring more accurate estimates of large-scale air-sea flux. NASA observing programs contribute unique data sets to advance toward this goal, notably the most accurate ocean surface wind velocity data so far (NSCAT; Seawinds), improved atmospheric temperature and humidity profiles data (AIRS/AMSU/HSB; ATMS); improved ocean surface temperature and total precipitable water measurements (MODIS; TRMM microwave imager; EOS Aqua/ASMR). NASA will support investigations aiming to improve the utilization of space-based and *in situ* measurements to derive and validate large-scale estimates of energy and water fluxes at the air-sea interface.

4.3.1.3 Mesoscale Weather Observation and Research

Quantitative precipitation forecast, using available *in situ* measurements and remote sensing data, is a principal scientific objective of the U.S. Weather Research Program (USWRP), as well as NASA's Earth system science program. Detailed diagnostic and model investigations of the structure and dynamics of mesoscale weather systems, as well as their relationship to the large-scale flow of the atmosphere, are needed for this purpose. Additionally, the scientific study of intense mesoscale weather systems (e. g. Hurricanes) and fast-developing severe weather phenomena (e. g. tornado-generating storms) is of paramount importance for weather forecasting and the protection of life and property, and a major scientific objective of the USWRP. In general, improved knowledge of the dynamics of convective cloud system will be needed in order to quantitatively assess vertical exchanges of momentum, heat and water that affect global climate, as well as atmospheric transport of chemical constituents through the troposphere.

Understanding the connections between global climate and weather is a central objective of this theme, requiring reliable characterization of mesoscale weather systems development, intensity and life cycle. So far, the most useful source of observational information for this purpose is the record of ocean surface wind data derived from space-based microwave scatterometer measurements (Seawinds) at a spatial resolution of 25km and wind accuracy of 2 m/s (see chapter 5: Ocean and Ice).

Geostationary Observing Systems

Field observation campaigns can provide comprehensive observations of the structure of individual mesoscale weather systems in a limited number of cases. Notwithstanding the value of such comprehensive data sets, continuous observation of a large atmospheric domain from geostationary platforms, such as the Geostationary Operational Environmental Satellites (GOES), offers a much faster means to determine the statistics of these scattered and short-life weather phenomena and constitute an essential tool for relating weather disturbances to large-scale circulation patterns. The NASA Instrument Incubator Program (technology development) and New Millennium Program (flight demonstration) have been tasked to improve upon the current remote sensing capabilities in geostationary or even more distant observing platforms. Two promising avenues for pioneering NASA contributions to weather system monitoring are:

- Observation of tropospheric temperature/moisture profiles, wind pattern and moisture inflow in the *far field* around weather systems, where the cloud cover is not solid. Such observations would be obtained from geostationary orbit by infrared atmospheric sounder instruments that could resolve the vertical structure of tropospheric water vapor.
- Diagnostics of convective cloud system development and life cycle, based on continuous observation of lightning flash rates, with special emphasis on tornado-generating storms and otherwise severe rain storms.

The first has been selected as the objective of the third New Millennium Earth observation technology demonstration mission (GIFTS). Successful development of this remote sensing capability can lead to more reliable prediction of fast developing severe weather phenomena. Considering the benefits of mitigating the heavy societal cost of severe weather events by extending the range of timely warning and the development cost of prototype instruments, application to operational environmental satellite systems is expected to follow.

Field Campaigns

The estimation of precipitation rates from active and passive microwave measurements is actually based on a cloud model simulation initialized with satellite observations of ice and liquid water in precipitating clouds. The validation of such rainfall estimation algorithms (or cloud system models) is based on model comparison with detailed field observations of cloud microphysical properties, cloud mesoscale structure, atmospheric temperature and moisture profiles.

The TRMM Ground Validation program, involving a series of high-flying aircraft campaigns over various tropical sites, is intended to obtain measurements similar to those provided by the satellite (at higher spatial resolution), in addition to *in situ* raingauge and surface-based meteorological radar observations. Data from TRMM ground validation case studies provide independent information on the total amount and vertical structure of precipitating water in convective and stratiform cloud systems, that can be directly compared to TRMM rain rate estimates. The field campaigns also provide the full range of measurements needed to refine and validate the TRMM retrieval algorithms. This effort is expected to continue, as appropriate, though the life of the TRMM mission and similar ground validation activities are expected to continue for a later Global Precipitation Mission.

In parallel, the investments made in the TRMM and similar ground validation program provide the means to carry out unique investigations of mesoscale cloud systems, notably tropical hurricanes. The Convection and Moisture Experiment (CAMEX) field study series, conducted by NASA in cooperation with the National Oceanic and Atmospheric Administration, collected observations of unequalled high-spatial and temporal resolution to characterize the 3-dimensional structure, motions and dynamics of successive Atlantic hurricanes during the 1998. The CAMEX program is thus emerging as a major scientific component of a multi-agency effort to observe tropical cyclone formation, motion and intensification, and improve the prediction of hurricane landfall. Study of hurricanes near landfall is a priority of the USWRP, a joint research effort of the US Navy, NASA, NOAA, NSF, and the academic research community. The overarching objective of the USWRP is to improve the accuracy and reliability of weather forecasts for high impact weather that can disrupt the functioning of society.

The program is expected to evolve toward dedicated field and model studies of critical weather systems over a full life cycle (principally by means of dedicated aircraft campaigns), including:

- Dynamical and microphysical processes in convective cloud systems associated with tropical storms, fronts, and monsoons, that can cause severe weather and flood,
- Model representation of precipitation processes in cloud-scale, mesoscale and global models.
- Impact of assimilating space-based observations of precipitation and associated properties on rainfall prediction skill in mid-latitude and tropical weather systems.

Field measurements will be complemented by the development of appropriate mesoscale atmospheric models (horizontal resolution on the order of 1-15km) and assimilation systems for model initialization using 3-dimensional air motion data, temperature and water vapor data, radar reflectivity and/or inferred microphysical properties, and surface rainfall. NASA will support an active program of field campaigns using unique NASA aircraft platforms and sensors, as a contribution to multi-agency studies of mesoscale weather processes.

4.3.2 CLOUDS AND RADIATION IN THE EARTH'S CLIMATE

The impact of clouds on the Earth energy balance is second only to that of water vapor. Clouds contribute half the planetary albedo, reflecting about 50 Watt/m^2 of incoming solar radiation back to space, while cloud absorption reduces by 20 Watt/m^2 the loss of terrestrial radiation to space (compared to 30 Watt/m^2 for all greenhouse gases other than water vapor). Even a modest error in predicted cloud cover could seriously impair model estimations of global climate change. It is generally recognized that clouds account for most of the remaining 1.5 - 4.5K uncertainty in model estimates of global warming that could result from a doubling of CO_2. The importance of this radiative effect justifies the high priority given to cloud-radiation feedback research by national and international scientific advisory bodies (notably the Intergovernmental Panel on Climate Change; IPCC, 1996). In addition to their impact on the planetary radiation balance, clouds govern radiative heating in the atmospheric column and radiation fluxes (especially solar radiation) reaching the Earth's surface.

Other particulate matter present in the atmosphere (aerosols) also has a distinct, albeit much smaller impact on the planetary radiation balance. The importance of aerosols in global climate change is related not so much to the absolute value of their contribution to the planetary radiation budget, but rather to changes that can be traced to anthropogenic sources. Accordingly, discussions of the diverse science issues arising with aerosols are grouped in Chapter 3, together with other climate forcing factors. (See section 3.3.2). On the other hand, aerosols also act as cloud condensation nuclei and may modify the optical properties of clouds: this indirect radiative forcing effect intimately involves cloud system dynamics and is considered part of cloud process research (Section 4.3.2.2).

4.3.2.1 Planetary Radiation Budget and Global Cloud Measurements

Considerable progress has been achieved by the NASA-sponsored Earth Radiation Budget Experiment (ERBE) since its launch 1984. ERBE measurements of broad-band radiation fluxes at the top-of-the-atmosphere (TOA) constituted the first major advance toward quantifying the radiative effects of clouds on a planetary scale and provided a very useful constrain on radiation transfer computations in climate models. Similar information, albeit with considerably lesser accuracy but more spatial and temporal detail, has been derived for the last 15 years from narrow-band visible and infrared radiometer data on polar-orbiting and geostationary operational meteorological satellites, as part of the International Satellite Cloud Climatology Project (ISCCP) organized by the World Climate Research Program, with contributions from NASA and other satellite operating agencies. The ISCCP collects and analyzes satellite radiance measurements for cloud system classification, estimation of cloud optical properties, and determination of diurnal, seasonal and interannual variations. Both data sets have been effectively used to improve the representation of clouds in climate models and understand their relationships to weather systems (ISCCP) and climatic variations (ERBE).

Several significant scientific problems remain to be addressed, notably the need for improved knowledge of the angular distribution of reflected solar radiation (needed in order to estimate total radiant energy fluxes on the basis of radiance measurements in one direction only). In this regard, major advances are expected from a series of advanced broadband radiometer instruments (CERES) on the Tropical Rainfall Measuring Mission (TRMM) and first two major EOS missions, leading to much reduced uncertainty on the terms of the planetary radiation balance (on order of 1 Watt/m^2). Additional supporting information will also be obtained from two Moderate-Resolution Imaging Spectro-radiometers (MODIS) on EOS Terra and Aqua (fractional cloud cover and cloud top optical properties), the Multi-angle Imaging Spectro-radiometer (MISR) on Terra (viewing angle diversity), and the Advanced Infrared Sounder (AIRS) on EOS Aqua (resolution of the infrared spectrum and correction on limb-darkening effects). Altogether, it is anticipated that major progress will be made during the next five years in determining the terms of the planetary radiation balance at the top of the atmosphere, thereby providing a definitive reference point for global climate model simulations.

In the long term, the extent to which continued broadband radiation flux measurements will yield further advances in the understanding of climate dynamics and radiative transfer in the Earth atmosphere is the subject of scientific discussion. Under any circumstance, the NPOESS program is planning to continue systematic broadband radiation measurements with CERES or a similar instrument on one of the two NPOESS spacecraft indefinitely in the future. Possibilities for flying a spare CERES instrument in order to maintain a continuous record through the interim period between EOS and NPOESS are being considered by NASA.

In addition, NASA will continue a strong research and data analysis program to extract the information contained in the wealth of narrow-band radiance measurements available from US and international observing systems. This may include radiance data processing and re-processing projects (such as ISCCP and the surface radiation budget climatology project) that provide valuable cloud diagnostics and derived radiation flux information, and support centers of scientific excellence in cloud and atmospheric radiation research.

4.3.2.2 Cloud, Aerosol and Radiation Process Research

The optical properties of clouds and aerosol are complex functions of number density, particle size and shape, physical state (liquid water or ice) and chemical composition in the case of aerosols. The impact of clouds on atmospheric radiation transfer and radiation flux divergence (radiative heating) depend strongly upon the 3-dimensional structure of cloud systems. Likewise, the radiative forcing caused by aerosols depends upon masking by clouds and the underlying surface albedo. In addition, significant indirect radiative forcing effect may be induced by certain classes of aerosol that act as cloud condensation nuclei. The presence of a higher density of condensation nuclei results in the formation of a larger number of smaller droplets, with longer residence time and enhanced optical depth for a given amount of liquid water. The duration of this cloud seeding effect on an evolving population of cloud droplets of increasing age and changing properties is not known. The connections between cloud microphysical processes and radiative properties are obviously quite complex and largely unexplored.

All currently existing measurements suffer from a common bias, inherent to the observation of radiances emerging from cloud tops. The parameters of most direct scientific interest – atmospheric heating and surface radiation fluxes – cannot be determined unambiguously from TOA radiance measurements, because different cloud layering within an atmospheric column may yield the same outgoing radiation flux at TOA (but very different surface fluxes). Thus, the scientific challenge in cloud and atmospheric radiation research is probing the vertical distribution and optical properties of cloud particles in the atmospheric column, in order to provide measurement-based estimates of radiation flux divergence instead of relying on climatological statistics or models. This is made possible by the emergence of active sounding sensors that can probe the vertical structure of the cloudy atmosphere.

Cloud, Aerosol and Radiation Research Satellite Missions

The highest emerging research priority identified by the radiation science community is to acquire globally sampled, vertically resolved observations of cloud particle density, physical nature (ice or liquid water) and optical properties, and to relate these properties to the weather systems that generated the clouds.

NASA is planning two Earth System Science Pathfinder missions that are specifically designed to address this problem through active profiling of cloud and aerosol particles in the atmosphere:

- PICASSO-CENA mission, a US/French satellite project to observe the lowest range of optical depths (aerosols and optically thin clouds) by means of a two-frequency backscatter lidar sensor and a high-resolution solar radiation (oxygen A-band) spectrometer.
- Cloudsat mission, undertaken with the support of the US Air Force and the Canadian Space Agency. Cloudsat will investigate the intermediate range of cloud thickness (non-precipitating stratiform clouds and light drizzle) by means of a millimeter-wave Cloud Profiling Radar and a similar A-band spectrometer. Heavy precipitating clouds are already being observed, up to 40° latitude, by the TRMM Precipitation Radar.

Considering the time and space variability of atmospheric water vapor and clouds, and non-linear relationships between these factors and radiation transfer, simultaneous observations in the same air column are required. The PICASSO-CENA and Cloudsat missions will be launched simultaneously in 2003 and fly in formation with the EOS Aqua spacecraft. This three-spacecraft observing system will achieve a major advance in the ability to observe radiation fluxes, the three-dimensional structure of aerosol layers and cloud systems (including sub-visible cirrus cloud layers), and to infer radiative heating in the atmosphere and at the surface. With this breakthrough in the global observation of cloud optical properties and distribution, considerable improvement is expected, during the next 5 years, in the ability to understand, quantify and model the radiative impact of clouds on climate and their relationship to weather disturbances.

On the other hand, detailed simultaneous observation of cloud condensation nuclei (aerosols) and cloud particle density, size and properties, which would be needed to determine the indirect effect of aerosols on cloud radiative properties and climate, are still beyond reach. This is a scientific challenge that can only be approached indirectly through modeling of cloud microphysical processes.

Field Campaigns and In Situ Measurements

One of the largest gaps in our understanding of cloud/radiation processes concerns extensive tropical cirrus clouds, their development, persistence and their ubiquitous effect on regional and global radiation budgets. High-altitude tropical cirrus systems, which dominate cloud radiative forcing in the tropics, result from the vertical transport of water by deep convective cloud clusters. The process produces a wide variety of upper-level clouds, ranging from thick precipitating anvil clouds and medium-thick (non-precipitating) clouds, to thinner cirrus that are a widespread feature of the tropics. Each of these cloud types exerts a different influence on the radiation budget and thus the climate response. Building on the heritage of the FIRE (First ISCCP Regional Experiment) and SUCCESS (Sub-Sonic Contrail and Cloud Effects Special Study) field campaigns, the Cirrus Regional Study of Tropical Anvils and Layers (CRYSTAL) program will address this gap in our understanding.

CRYSTAL consists of three coordinated components: an intensive field campaign (2001), a cloud modeling program and data analysis studies. CRYSTAL principally address two scientific questions:

- Upper tropospheric distribution of ice particles and water vapor and associated radiation fluxes on storm and cloud system scales.
- Upper tropospheric cloud generation, re-generation, and dissipation mechanisms, and their representation in both regional-scale and global climate models.

Intensive field studies, involving the coordinated use of multiple aircraft platforms, surface, and satellite measurements, are an essential component of the cloud/radiation research strategy and the validation of forthcoming EOS measurements (CERES, MODIS and MISR) and relevant Earth System Science Pathfinder missions.

Cloud, Precipitation and Radiation Transfer Models

Accurate representation of cloud-climate feedback in climate models is indispensable for predicting the possible consequences of human-induced environmental changes. Such feedback mechanisms cannot be directly observed; rather they must be diagnosed from global observations of energy and water exchanges within the climate system, and climate model studies that relate flux variations to specific processes. On account of expected improvements in observing and data processing systems, the research strategy will rely on a hierarchy of models, ranging from cloud process-resolving models to general circulation models.

Microphysical models address the formation and growth of cloud particles in a saturated-vapor environment produced by atmospheric motions, including the roles of aerosols as condensation nuclei and of cloud particle freezing-melting processes. More work is needed to study the role of aerosols and the nature of aerosol processes in high altitude or polar ice clouds, and in mixed-phase situations. *Dynamical models* are used to investigate cloud particle growth and subsequent fallout, and their evaporation below cloud-level or the generation of rainfall. *Radiation transfer models* are the primary tool to study the effect of clouds on the radiative heating of the surface and atmosphere.

The ultimate objective is to develop and exploit comprehensive *Process-Resolving Cloud System Models* that explicitly represent the fundamental microphysical processes (such as the indirect effect of aerosols on cloud particle growth and radiative properties), as well as precipitation generated by the cloud. Such models can be compared directly to single-column parametric formulations of cloud processes in climate models. It is envisioned that cloud-resolving models will first be verified by comparison with detailed field measurements in various meteorological situations, and then compared with mesoscale models that reproduce the same meteorological fields. Finally, global satellite observations will be used to identify ensembles of similar cloud systems that can serve as a basis for generalizing results from individual case studies to climate statistics, and for validating the simplified representations of cloud processes in atmospheric general circulation models and climate models.

4.3.3 LAND SURFACE PROCESSES AND HYDROLOGY

The hydrological element in the Global Water and Energy Cycle research theme aims to understand the role of the terrestrial hydrosphere (and biosphere) in the Earth climate system. Surface hydrological processes influence weather and climate locally at all time scales, and large errors in surface temperature forecasts can be traced to poor handling of latent heat exchanges associated with evaporation, soil freezing or thawing. Land surface processes also influence summer precipitation over large regions in the interior of continents. Likewise, snow and frozen ground in late spring appears to have a lasting affect on weather patterns and, at high latitudes, the CO_2 intake of the boreal forest. In this manner, land hydrological processes may induce positive climate feedback that could enhance extremes of drought, or heavy precipitation and flood.

Equally significant is the governing role of land hydrological processes in the partitioning of rain water and snowmelt among evaporation, ground storage, and run-off to the river system. Understanding and modeling these processes reliably is a prerequisite for quantitative application of climate predictions to water resource management. In general, water transport and land-atmosphere-ocean teleconnections are not well understood. The principal obstacles hampering progress are insufficient large-scale observations, poorly resolved representations of hydrological processes in climate models, and the lack of comprehensive data sets for use in validating model formulations. NASA plans to address these deficiencies through better utilization of currently available land surface data, process model development and verification with intensive field measurements and aircraft observations, and large-scale diagnostic studies based (mainly) on satellite observations.

4.3.3.1 Experimental Land Hydrology Observing Missions

It is recognized that scientific questions regarding the role of terrestrial hydrology in the climate system cannot be answered on the basis of *in situ* measurement alone - the historical record is too short and the required observations are too extensive and impractical from a logistical standpoint. Effective use of remote sensing data is crucial to make progress in global water cycle research. It is a fact, however, that soil properties and soil water processes remain largely shielded from remote sensing based on the detection of electromagnetic signals, as the penetration depth of microwave radiation in wet soil is only a few centimeters. NASA recognizes these technical difficulties and gives high scientific priority to developing the means for global measurement of essential hydrological quantities from space, principally precipitation and near-surface soil moisture. In combination with additionally proposed experimental measurements of snow, soil freezing/thawing and rivers or lake stage, the possibility exists to estimate all components of the terrestrial water budget at regional to continental scales directly from observations.

Global Precipitation Mission

Knowledge of precipitation at the time and space scales of storms (about ten kilometers and one to several hours) is essential for understanding the impact of weather on land surface hydrology. Considerable progress in understanding the dynamics of precipitating systems is also needed for quantitative precipitation forecasting and climate prediction. Satellite-based remote sensing offers the only practical option for acquiring globally consistent precipitation data sets needed to test and improve weather and climate models, and to drive large-scale hydrological models that can infer surface moisture, ground water storage and run-off over the global land surface (see Box 4).

Soil Moisture Research Mission

At present soil moisture is the only primary hydrologic variable that cannot be measured at large spatial scale. Scientific evidence shows that soil moisture is the most significant indicator of the state of the terrestrial hydrologic system, and is the governing parameter for partitioning rain water among evaporation, infiltration, runoff. Soil moisture also plays a critical role in vegetative processes and provides the critical link between the physical climate system (water and energy) and biogeochemical cycles. Recent research has demonstrated that knowledge of soil moisture enhances predictability of summertime precipitation over much of the U.S.

The unresolved problems in measuring soil moisture from space are obtaining useful signals under a substantial vegetation canopy and reaching a useful depth within the uppermost soil layer while, at the same time, achieving useful spatial resolution (on the order 10-30 kilometers) and temporal sampling (repeat intervals of 1 to 3 days). Large real or synthetic apertures are required to meet these requirements in the low-frequency range of the microwave spectrum. Several alternative techniques will be studied by NASA for remote sensing of soil moisture from space, including 2-dimensional aperture synthesis adopted by the European Space Agency for a Soil Moisture and Ocean Salinity (SMOS) Earth Explorer mission planned to be launched in 2004.

Another potentially promising measurement concept is the gravimetric determination of changes in soil water storage, based on extremely precise observation of time-dependent changes in the Earth gravity field. The experimental GRACE gravity mapping mission will explore the extent to which this concept is applicable to land hydrology.

Cold Climate Land-Surface Process Research Mission

Cold season processes (snow extent and water equivalent, soil freezing and thawing) strongly affect the short-term hydrologic dynamics on the scale of river basins, and land-atmosphere feedback at continental scales. In the interior of North America and Eurasia, and in high altitude mountain areas, much of the annual precipitation contributing to streamflow occurs as snow during the winter months, with evident effects on the seasonal cycle of runoff. The freeze/thaw status of the soil surface determines the relative amounts of snowmelt and precipitation that contribute to runoff versus infiltration; differences in albedo between snow-covered and snow-free areas result in large changes in net radiation during the thaw period. While these processes are understood at local-to-catchment scales, available observations are inadequate to quantify the role of snow and frozen ground in the physical climate system. Research under NASA's Boreal Ecosystem-Atmosphere Study (BOREAS) has shown that the onset of springtime thaw significantly influences the annual uptake of carbon by boreal forests, demonstrating the importance of observing the freeze-thaw transition to understand the interacting water, energy and carbon cycles at high latitudes.

Surface Water Level Monitoring Mission

Although river stage height can be conveniently observed *in situ* for small to moderate streams, the discharge of many of the world's major rivers is not currently being monitored, or the data are not available to the scientific community. River discharge and changes in inland lake levels are integrators of runoff; the measurement of these basic hydrologic variables in near real-time would be an invaluable aid in validating climate and water resource predictions. River discharge is also an important driver of ocean circulation. Knowledge of changes in water storage by inland water bodies and their impact on regional and continental water budgets is also deficient due to a lack of observations. A number of tests, carried out with the Topex/Poseidon radar altimeter, demonstrated the ability to monitor level changes in large rivers and inland water bodies. Precision radar altimeters, currently being developed for oceanographic or polar research purposes are potentially capable of detecting very small changes (on the order of a few centimeters) in the stage of inland water bodies, but cannot provide the required short sampling interval

(1 to 3 days). The potential also exists for Doppler lidar measurement of river surface velocity and, in combination with river stage data, direct estimation of river discharge from satellite measurements.

4.3.3.2 Land Surface Process Studies and Field Campaigns

NASA has a long history of supporting hydrological field experiments, from the seminal HAPEX study in France to HAPEX-Sahel in sub-saharan Africa, FIFE in the Central Plains, and BOREAS in the Arctic forest. These intensive field studies serve three main purposes: (1) improvement of hydrologic process parameterization in mesoscale and general circulation models; (2) development and testing of remote sensing instruments and algorithms; and (3) development of procedures for assimilation of remote sensing data by process-resolving models. Currently, hydrological and joint atmospheric-hydrologic field studies, involving intensive *in situ* measurements and airborne remote sensing, constitute a very productive element of the NASA hydrology research program.

As part of a broader science strategy to understand the water and energy cycle at regional and continental scales, NASA also participates in more ambitious continental-scale experimental projects, which encompass the Mississippi river basin (GEWEX International Continent-scale Project) in the USA and the Amazon river basin in Brazil (Large-scale Biosphere-Atmosphere experiment). These continental-scale projects provide a research framework to test scaling process parameterizations and remote sensing algorithms developed from NASA field-scale experiments. These continental experiments, when combined with long-term data sets, should provide increased understanding of the mean state and variability of the water and energy budget terms at regional scales, thus providing a foundation for global analyses. NASA will continue to support fundamental process studies based on intensive *in situ* and aircraft observation, as appropriate, and will invest in an active program of field campaigns to test new remote sensing methodologies and instruments, in preparation for future experimental satellite missions.

4.3.3.3 Large-scale Hydrologic Diagnostic Studies and Modeling

Another important thrust is a program of large-scale diagnostic studies, based on existing global data sets, to investigate the seasonal, annual and interannual variability of water and energy cycles at continental-to-global scales. This effort addresses the central objective of the international GEWEX program and is the focus of EOS research on terrestrial hydrology. This research approach is particularly relevant for enhancing the reliability of streamflow predictions and related hydrologic forecasts on time-scales of hours to seasons, thus providing possibilities for transferring knowledge from research projects to water supply, flood control, and drought management applications.

Global and continental scale diagnostic studies are an effective means for integrating available measurements, physical understanding and model products covering many space and time scales. They address issues such as the impact of local and remote forcing on the terrestrial hydrological cycle, feedback to the atmosphere through changes in surface soil moisture, or the role of snow cover in modulating weather on seasonal time scales. A specific objective is exploring the connections between synoptic-scale atmospheric phenomena and small-scale hydrologic processes, developed through site-specific field experiments such as FIFE and BOREAS. Diagnostic studies also constitute a good basis for improvement of data assimilation algorithms, evaluation of data assimilation products (especially in data sparse regions), and advances in hydrologic prediction and water resources management.

Satellite data that have been used for large-scale studies include long-term records of atmospheric temperature and moisture, vegetation, temperature, and precipitation (e. g. SSM/I Pathfinder data reprocessing projects; Global Precipitation Climatology Project). An example of a global diagnostic approach is the GEWEX Global Soil Wetness study organized by the International Satellite Land-Surface Climatology Project (ISLSCP), with the support of NASA and several environmental research agencies. New developments in remote sensing algorithms from the TRMM and EOS programs are expected to yield major advances in the derivation of the basic data sets (precipitation, net surface radiation, near-surface humidity and air temperature) used for these and future more ambitious diagnostic studies, which include:

- Development of hydrologic models which can link hydrological processes across all scales. Application at large spatial scales requires the estimation of model parameters related to land surface characteristics (vegetation, soil, topography) based on remote sensing data, such as vegetation classification, vegetation indices, topography and soil types.
- Evaluation of the ability of hydrologic models to reproduce the observed natural variability, and the sensitivity of model outputs to modeling assumptions. The GEWEX Project for Inter-comparison of Land-surface Parameterization Schemes (PILPS) is an example of a current study in this domain. Diverse climate regimes need to be studied to gain confidence in model-derived water and energy budget information.
- Application of hydrologic models to assess the impact of improved land surface process formulations on hydrologic forecasting, weather prediction and water resources management.

4.3.4 ATMOSPHERIC DATA ASSIMILATION AND MODELING

The analysis of large data streams derived from global observation of the Earth from space is a principal concern of NASA. Four-dimensional data assimilation, using a time-dependent model of the atmospheric circulation, is the principal tool for integrating observations from different sources and producing a coherent picture of Earth system dynamics (circulation), thermodynamics (energy fluxes), hydrology (water fluxes) and biogeochemistry (ozone, carbon dioxide, etc.). In general, space observation offers unequaled global and uniform coverage, but only incomplete information about the phenomena under study. Combining remote sensing observations and *in situ* measurements, in a manner consistent with the dynamical, physical and chemical relationships that govern the system, is a powerful means of extracting the full information content of the observations.

Data Assimilation as an Operational Analysis Tool

Four-Dimensional Data Assimilation (4DDA) optimally combines diverse and incomplete observations with short term forecasts from a geophysical model to produce a succession of snapshots, each forming the best possible analysis of the state of the system under observation. The primary role of 4DDA is to deliver estimates of the relevant geophysical or chemical variables in the form of complete gridded fields as "data products" that can be used for a variety of scientific applications, from diagnostic studies of global Earth system processes to ancillary information for remote sensing retrievals. The assimilation model maintains dynamical, physical, and chemical consistency of the primary prognostic variables, produces internally consistent estimates of diagnostic quantities such as heating rates, surface fluxes and vertical motion that cannot be measured directly, and provides a means to assess the quality of observational data.

The reanalyses of past meteorological data conducted by three major center – the European Center for Medium-range Weather Forecasts, the NOAA National Centers for Environmental Prediction (NCEP) and the NASA Data Assimilation Office (DAO) - have provided an indication of the potential applications of 4DDA to climate research. The weaknesses as well as strengths of current 4DDA products largely reflect the past priorities of numerical weather prediction. The strengths lie in the representation of the mass and wind fields which most directly impact short and medium range weather forecasts, while the weaknesses are found in the representation of the hydrological cycle and in the vertical component of the tropical circulation. Currently, residual biases in estimated net surface energy and water fluxes are too large to reliably derive oceanic transport of heat and fresh water. Estimates of precipitation minus evaporation over land show significant discrepancies with independent river discharge measurements. Reducing systematic errors to a level that allows using data assimilation products directly for climatological applications constitutes the principal challenge to the DAO and associated researchers.

NASA will continue to invest in the operation and improvement of the system implemented by the DAO with the objective to match and improve upon the international state-of-the-art in extracting maximum information from satellite observation. The short-term objective is to implement a higher resolution version of the current assimilation system (global 1°x 1° grid) that realistically resolves meteorological fronts and other dynamically significant small-scale features of the atmospheric circulation. Next steps include the testing and implementation of a new dynamical core model developed in collaboration with the National Center for Atmospheric Research. The new model will use a modern (semi-lagrangian) advection algorithm that conserves flux quantities and provides an order-of-magnitude acceleration in computing speed over the current system. The model is also designed to allow convenient interchange of physical parameterization schemes with those developed by the climate modeling community. NASA encourages and will support the development of such cooperation with the academic community and partner agencies, particularly NOAA/NCEP.

Data Assimilation as a Learning Tool

As highlighted in the National Research Council report on *Four-dimensional Model Assimilation of Data* (1991), data assimilation is also "a systematic, structured, and open-ended learning process". By continually confronting the geophysical model with observations, 4DDA quantifies the mismatch between observations and model forecasts, and provides clues for further model improvements. This interactive optimization of model and data analysis is perhaps the single most important benefit of data assimilation in a research mode. This linkage has been successfully exploited by Numerical Weather Prediction centers to improve short term weather forecasts. The challenge for the broader Earth science community is to build upon this success by extending the application of assimilation systems to all relevant components of the Earth system, and developing 4DDA methodologies capable of exploiting non-standard measurements (especially new space-based observations).

In this perspective, the NASA global data assimilation program will be the principal means for integrating knowledge gained about the physics of individual atmospheric and hydrologic processes into a coherent dynamical representation of the global climate system and, eventually, the full Earth system. Each improvement in the formulation of 4DDA model dynamics and physics is a step toward quantitative understanding of the climate system and its response to external forcing. NASA will encourage closer interaction between discipline-oriented process research (theoretical studies, field campaigns, and process-resolving models) and global data assimilation activities across the range of geophysical and chemical variables measured routinely by operational and research observing systems. In particular, NASA will encourage diagnostic analysis of global data assimilation products and direct comparison of deterministic (short-term) predictions with observations of specific weather phenomena at the same location and time.

Assessment of Weather System Predictability

The ability to derive useful predictions of regional climate fluctuations is limited ultimately by the ability to effectively forecast probable impacts on regional scales. Systematic data assimilation and experimental ensemble predictions of the atmospheric circulation (in a delayed mode, using observed surface boundary conditions) constitute the ideal means to test the statistical significance of linkages between global climate variations and changes in regional weather patterns and hydrologic regimes. The latter objective has yet to be addressed by DAO and constitutes a major scientific challenge in the coming five years, with a potential for scientific findings and practical applications commensurate with NASA's resource investment. Scientific collaboration with operational weather prediction centers will be especially favored in the pursuit of this scientific goal.

Technical Challenges

A key requirement for effectiveness of 4DDA systems in climate and global change studies is the ability to resolve all significant scales of motion in the atmospheric circulation. This requirement implies quite high spatial resolution and makes 4DDA techniques very computer intensive. The 1991 NRC report suggested that global assimilation systems should have 100 km or better horizontal resolution with about 30 levels in the vertical dimension, in order to resolve important boundary layer and stratospheric phenomena. Current global assimilation systems meet or exceed these specifications; mesoscale models with even higher spatial resolution have been developed for realistic simulation of convective and stratiform cloud ensembles. Both kinds of numerical simulation stress existing computing capabilities.

In general, the demand for computing resources for such cutting-edge numerical tasks cannot be met by the acquisition of faster and more powerful computer equipment alone. A major investment is needed in numerical analysis, algorithm development and software optimization. Transition to more efficient numerical codes, even at the expense of programming convenience for scientists, is a necessary evolution that will be required of any world-class modeling and data assimilation center. It is the intent of NASA to promote the necessary investments in advanced software and numerical code optimization for data assimilation models and climate models alike. In order to accelerate the pace of development, expanded cooperation will be sought with academic institutions, government laboratories, and operational weather prediction centers.

Scientific Challenges

The principal current scientific challenge involved in atmospheric circulation modeling is the development of parametric formulations of unresolved small-scale processes that are consistent with higher model resolution. In general, more detailed, physically realistic, and also more complex "parameterization" schemes are required to match the higher spatial resolution of the basic dynamical model. Progress in this domain will depend upon advances in process observation and process-resolving models, as well as the vigilance of atmospheric circulation and climate modeling groups for exploiting the latest advances for the improvement of process parameterization (see section 3.3.4.1). Of particular importance in the next few years will be Cloud Ensemble Models that allow explicit representation of small-scale dynamics and microphysics, with emphasis on realistic simulation of precipitating cloud systems.

4.4 LINKAGES

Linkages with other NASA programs

The principal scientific linkages of the Global Water and Energy Cycle research theme within the NASA program are with Earth System and Observation and Modeling (Chapter 7). The GWEC component of the NASA Earth Science program provides improved physical understanding and modeling (parameterization) of atmospheric and hydrologic processes in the context of global climate studies, and also provides essential observing programs and products for climate diagnostic studies. Important linkages also exist with the Atmospheric Chemistry program, concerning the atmospheric transport and mixing of chemical species and the indirect effects of aerosol on cloud optical properties, precipitation and radiation transfer (Chapter 3). The connection with the Ecosystem Biology and Biogeochemistry program lies principally in the two-way interaction of terrestrial ecosystems and land hydrologic processes (Chapter 2). In addition, NASA supports research on the impact of Climate on Health through the provision of relevant global observational data sets and analyses products.

Linkages with other US agencies (Global Change Research Program)

The NASA Global Water and Energy Cycle research program has very active connections with at least three partner agencies within the US Global Change Research Program. NASA and the National Science Foundation (NSF) cooperate in a number of investigations focused on the study of physical atmospheric processes, especially the development of cloud process-resolving models (also known as Cloud Ensemble Models) and atmospheric general circulation models. The latter effort is led by the NASA Data Assimilation Office and the National Center for Atmospheric Research.

NASA interacts with the National Oceanic and Atmospheric Administration (NOAA) at a multiplicity of levels. On the technical level, NASA has historically been at the origin of most instruments used in NOAA's operational polar-orbiting or geostationary environmental satellite programs. Currently NASA discharges program management responsibility for the acquisition of operational environmental satellites on behalf of NOAA. The decision to merge the operational polar-orbiting meteorological satellite programs of NOAA and DOD has altered this historical relationship but NASA is engaged in the development of advanced instrument technologies that will be infused in the emerging National Polar-orbiting Environmental Satellite System (see Box 3).

NASA and NOAA also cooperate in a wide variety of research projects. NASA brings unique global observation tools and airborne observing assets to the NOAA-led U.S. Weather Research Program and the NASA Data Assimilation Office cooperates with NOAA's National Centers for Environmental Prediction in addressing the quantitative rainfall prediction research objective of that Program. NASA and the NOAA Office of Global Programs and NASA also co-sponsor the GEWEX Continental-scale International Project over the Mississippi river basin.

Finally, NASA is a major scientific partner of the Department of Energy Atmospheric Radiation Measurement Program through joint fundamental studies, cooperative instrument calibration activities, and field measurement campaigns involving NASA's airborne remote sensing facilities.

International linkages

The NASA Global Water and Energy Cycle program component is closely aligned with the scientific goals and scientific strategy of the Global Energy and Water Cycle Experiment (GEWEX) program of the World Climate Research Program, and the Biospheric Aspects of the Hydrological Cycle project of the International Geosphere-Biosphere Program. Historically, NASA played a leading role in the development of GEWEX and still relies on this international program to nurture cooperative relationships with the worldwide atmospheric science community. NASA is a major partner in most GEWEX projects, from the International Satellite Cloud Climatology Project, initiated in 1982, to the Global Water Vapor Project undertaken in 1999.

Several major bilateral cooperative programs or projects have also been developed by NASA with foreign agency partners, notably Japan (joint implementation of the Tropical Rainfall Measuring Mission and a future Global Precipitation Mission; realization of the Advanced Microwave Scanning Radiometer on EOS Aqua), France (joint realization of the PICASSO-CENA Earth System Science Pathfinder mission) and Canada (participation in the Cloudsat Earth System Science Pathfinder mission).

4.5 REFERENCES

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